LA-UR -82-1134

CONF-820415--5

TITLE: DATA ANALYSIS FOR NEUTRON MONITORING IN AN ENRICHMENT FACILITY

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LA-UR--82-1134

DE82 014052

SUBMITTED TO: The 4th Annual Symposium on Harmonization and Standardization, Petten, The Netherlands, April 27-29, 1982; sponsored by ESARDA

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FORM NO 836 R4
ST NO 2629 5/81

means for timely detection of anomalies in cascade area operations. Further, where a sufficient number of these monitors are located throughout the cascade area, the source of the anomaly may be localized. The proposed analysis procedure estimates the true neutron level from the noisy measurements and detects when that level has increased sufficiently that an anomaly should be declared. This paper discusses the application of statistical filtering to neutron signal estimation and statistical hypothesis testing to detect abnormal signal increases. The hypothesis testing procedures are structured to control the detection and false-alarm probabilities.

Detection of HEU production by the proposed neutron monitoring system is considered to be a problem in statistical hypothesis testing. The hypothesis H_0 of a neutron level indicating normal operation is tested against the alternative hypothesis H_1 of an increased neutron level. Testing these hypotheses require the conditional probability densities of the neutron measurements $Z_1, \ldots, Z_N$ under each hypothesis. If H_0 is true, the probability density is $p[Z_1, \ldots, Z_N|H_0]$; similarly, if H_1 is true, the probability density is $p[Z_1, \ldots, Z_N|H_1]$. A test procedure for deciding between H_0 and H_1 is the probability ratio test.[3] The probability ratio for the measurement sequence is

$$PR(N) = \frac{p[Z_1, \ldots, Z_N|H_1]}{p[Z_1, \ldots, Z_N|H_0]}$$

This ratio is a number that measures the relative likelihood of the two hypotheses given the measurements. Larger values of PR(N) favor H_1 and smaller values favor H_0. The test procedure

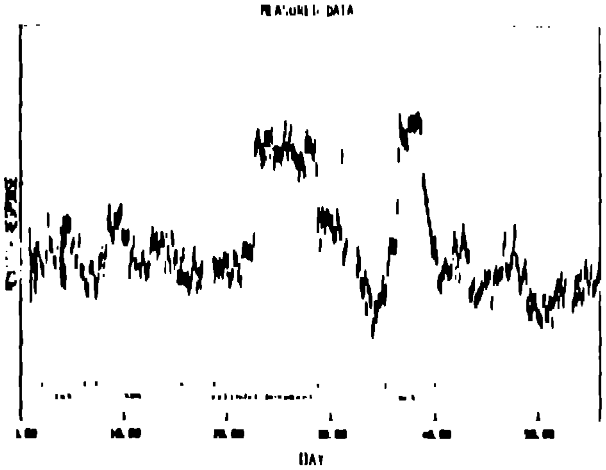

Fig. 1. Experimental data.

consists of comparing the probability ratio to an upper threshold TU and a lower threshold TL and applying the decision rule

accept H_1 when $PR(N) \geq TU$

accept H_0 when $PR(N) \leq TL$

and take another measurement and continue testing otherwise. When the hypotheses H_0 and H_1 are simple (they completely specify the conditional densities), the probability α (false-alarm probability) of accepting H_1 when H_0 is true and the probability β (miss probability) of accepting H_0 when H_1 is true are approximated by defining the thresholds

$$TL = \frac{\beta}{1 - \alpha} \quad \text{and} \quad TU = \frac{1 - \beta}{\alpha} \quad .$$

The formulation of the problem of detecting HEU production leads to the composite hypotheses

$$H_0 : \mu = \mu_0$$

and

$$H_1 : \mu > \mu_0 \quad ,$$

where μ_0 is the expected neutron measurement when H_0 is true and μ is the true neutron level. The usual way of treating the probability ratio test when hypotheses are composite is to form the generalized probability ratio

$$GLR(N) = \frac{\underset{\mu > \mu_0}{\mathrm{Max}} \ p[Z(N)|\mu]}{\mathrm{Max} \ p[Z(N)|\mu_0]} \ .$$

4. Statistical Filtering

Filtering[4] is a method for estimating the current value of a signal using noisy measurements of the signal. Applying this method to estimate the neutron signal from the uranium inventory of enrichment centrifuges requires an estimate of the neutron background measured by the detector. For this analysis the remote monitor background measurements were used to estimate the background for the centrifuge monitor. The measurement model for the remote monitor is

$$X_N = BG_N + \alpha_N \quad ,$$

where BG_N is the true but unknown background at the remote monitor and α_N is the measurement error. The error model for the centrifuge monitor is

$$Y_N = S_N + (a_N * BG_N + b_N) + \beta_N \quad ,$$

where Y_N is the measurement, S_N is the neutron signal from the centrifuges, $a_N*BG_N + b_N$ expresses an assumed time-varying linear relationship between the background at the remote and centrifuge monitors, and β_N is the measurement error. Estimating the background at the centrifuge monitor by $\hat{a}_N*X_N + \hat{b}_N$, where $\hat{a}_N, \hat{b}_N$ are estimates of a_N, b_N, and subtracting this from Y_N gives

$$Z_N = S_N + \gamma_N \quad ,$$

where γ_N is an error term that depends on α_N, β_N, and the uncertainty in estimating the coefficients a_N, b_N. The statistic Z_N is the object of the filtering procedures to estimate S_N.

The Kalman filter provides an estimate of the true value of a signal that is embedded in noise. Application of the method requires a model of the signal as a function of time and a model of the noisy observations of the signal. For this problem the signal is assumed to be constant

$$S_{N+1} = S_N \quad ,$$

and the observation model is

$$Z_N = S_N + \gamma_N \quad , \tag{1}$$

where γ_N is the measurement error. The only knowledge of the signal is through the noisy measurement relationship in Eq. (1).

The filter estimate of S_N is a weighted linear combination of the observations Z_1, ..., Z_N. This linear estimate can be expressed in the recursive form

$$\hat{S}_N = \hat{S}_{N-1} + K_N(Z_N - \hat{S}_{N-1}) \quad ,$$

where $\hat{S}_N$ is the signal estimate at time N. The filter gain K_N is calculated from

$$K_N = \frac{V_N}{V_N + W_N} \quad ,$$

where V_N is the variance of the estimate $\hat{S}_N$ and W_N is the variance of γ_N.

The Kalman filter method provides a minimum-variance, unbiased estimate of the true neutron signal from the centrifuges. When his estimate exceeds the neutron level for normal enrichment by twice the standard deviation of the estimate, there is an indication of an anomaly. However, the decision between H_0 and H_1 should be made using the probability ratio test that allows control of the error probabilities. The Kalman filter method is used to estimate the unknown quantities in the conditional probability densities in the probability ratio.

5. Data Analysis Results and Conclusions

The experimental data in Fig. 1 have been analyzed using both filtering and hypothesis testing procedures. Filtering of the data is represented in Fig. 2, which is the Kalman filter estimate of the neutron signal from the centrifuges. The estimate is centered at the 12 standard deviation error bars. Periods of increased enrichment are identified as positive deviations of the signal estimate by more than 2 standard deviations from the zero neutron signal le

The probability ratio for deciding between H_0 and H_1 is plotted in Fig. 3. Upper decision thresholds have been selected for approximate false-alarm rates of 0.01 and 0.001. When the probability ratio exceeds the upper threshold, detection of an anomaly is declared. Enrichments of 52 and 90% are easily detected at the 0.001 level. Enrichments of 20% could be detected at a false-alarm rate somewhat higher than 0.01.

These results suggest that statistical filtering and hypothesis testing procedures can be useful to an inspector for extracting information about facility operation from noisy measurement data. The filtering methods can estimate neutron signals from enrichments near 20%, and hypothesis testing procedures can detect enrichments near 20% with a false-alarm rate between 0.01 and 0.001 per year.

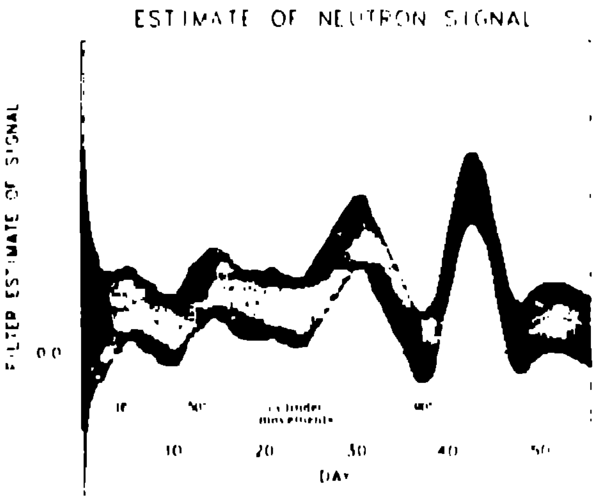

Fig. 2. Filtered data.

6. References

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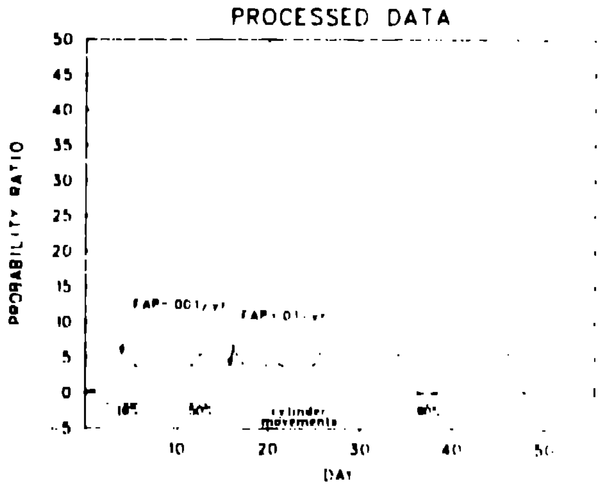

Fig. 3. Probability ratio test results.